ANALYSIS OF TOTAL HARMONIC DISTORTION AND SWITCHING LOSSES OF PWM IN GRID-CONNECTED PHOTOVOLTAIC SYSTEM

SYAHIERAH ELIYA BINTI SABRI

MASTER OF SCIENCE

UNIVERSITI MALAYSIA PAHANG

SUPERVISOR'S DECLARATION

We hereby declare that we have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

____

(Supervisor's Signature)

Full Name : IR DR MUHAMAD ZAHIM BIN SUJOD

Position : SENIOR LECTURER

Date :

____

(Co-supervisor's Signature)

Full Name : DR MOHD SHAWAL BIN JADIN

Position : SENIOR LECTURER

Date :

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

____

(Student's Signature)

Full Name : SYAHIERAH ELIYA BINTI SABRI

ID Number : MEE16010

Date :

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SYAHIERAH ELIYA BINTI SABRI

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ABSTRAK

Sistem fotovoltaik (PV) menjadi pilihan tenaga alternatif terbaik untuk menjana elektrik yang boleh menggantikan sumber bahan api dan pada masa yang sama tidak memudaratkan persekitaran. Sistem PV yang disambung ke grid (GCPV) membekalkan tenaga arus ulang alik (AC) yang dijana ke grid utiliti untuk diagihkan kepada pengguna. Dalam sistem GCPV, penukar arus terus (DC) kepada AC adalah suatu kemestian tetapi merupakan beban tidak linear yang menjana lebih banyak jumlah herotan harmonik (THD) ke dalam sistem kuasa elektrik. Harmonik yang dijana oleh sistem PV akan menurunkan kualiti grid kuasa dan memberi kesan terhadap kebolehpercayaan dan keselamatan. IEEE Std 519-1992 dan piawaian Tenaga Nasional Berhad (TNB) menggariskan THD perlu kurang dari 5% dalam kadar keluaran penukar DC kepada AC pada kabel yang disambung ke titik gabungan sepunya (PCC). Disamping itu, tahap sinaran suria di Malaysia adalah berbeza sepanjang hari serta sepanjang tahun. Kesan tahap sinaran suria yang rendah akan menyebabkan keluaran susun atur PV rendah dan masukan penukar DC kepada AC secara relatif menjadi rendah. Penukar DC kepada AC menunjukkan tidak kelinearan yang besar apabila penukar DC kepada AC beroperasi dengan masukan kuasa rendah ketika sinaran suria berada pada tahap rendah. THD dalam sistem GCPV dipengaruhi oleh tahap sinaran suria kerana hubungan antara tahap sinaran suria dan THD adalah berkadar songsang. Tambahan pula, perkaitan utama yang lain dalam sistem GCPV adalah kehilangan pensuisan pada alat pensuisan dalam penukar DC kepada AC. Keberkesanan sistem boleh ditingkatkan dengan melaraskan kehilangan pensuisan serendah mungkin. Teknik Pemedulat Pulsa Lebar (PWM) mempunyai kelebihan tersendiri seperti mudah dilaksanakan dan dikawal, serasi dengan pemproses mikro masa kini, tiada komponen tambahan diperlukan bagi mengawal voltan keluaran dan akhir sekali, harmonik lebih rendah boleh dikurangkan atau dihapuskan. Dalam kajian ini, objektif utama adalah untuk mengendalikan kajian bagi mengurangkan harmonik dan kehilangan pensuisan dalam sistem GCPV. Model sistem GCPV MATLAB/Simulink dipilih sebagai platform untuk melaksanakan PWM berterusan (CPWM) dan PWM tidak berterusan (DPWM) dalam pengawalan penukar DC kepada AC bagi mengkaji kesan pilihan ulangan pensuisan PWM ke atas THD dan prestasi kehilangan pensuisan pada tahap sinaran suria yang berbeza. Bilamana teknik-teknik ini dibandingkan, didapati CPWM ternyata sebagai pilihan penyelesaian terbaik. Hal ini disebabkan oleh nilai THD yang rendah diperolehi apabila CPWM dilaksanakan dalam kawalan penukar DC kepada AC. Tambahan pula, THD apabila DPWM dilaksanakan adalah lebih tinggi berbanding CPWM pada semua tahap sinaran suria. Nilai ulangan pensuisan yang bersesuaian pada tahap sinaran suria yang berbeza yang memenuhi piawaian keperluan THD serta kehilangan pensuisan yang minimum dicadangkan dalam tesis ini. Nilai ulangan pensuisan yang bersesuaian bagi setiap julat tahap sinaran suria adalah $f_{sw}1$ = 12600.00 Hz semasa 200 – 400 W/m², $f_{sw}2$ = 5000.00 Hz semasa 401 – 600 W/m², $f_{sw}3$= 1746.00 Hz semasa 601 – 800 W/m² dan $f_{sw}4$ = 1545.50 Hz untuk 801 – 1000 W/m² tahap sinaran suria. Sementara itu, DPWM memerlukan ulangan pensuisan yang tinggi bagi mencapai piawaian THD dan hasilnya adalah mendorong kepada kehilangan pensuisan yang tinggi dalam sistem. Penemuan utama dalam penyelidikan ini adalah pemilihan ulangan pensuisan PWM yang bersesuaian boleh mengurangan THD pada tahap sinaran suria yang berbeza.

ABSTRACT

Photovoltaic (PV) system becomes the best alternative energy choice to produce electricity that can replace fuel resource and at the same time not harmful to our environment. Grid-connected PV (GCPV) system supply the AC power generated to the utility grid then distributed to the consumer. In a GCPV system, an inverter is a mandatory, but it is a non-linear load that generates more total harmonic distortion (THD) into the electrical power system. Harmonic generated by the PV system may downgrade the quality of power grid and affect the reliability and safety. IEEE Std 519-1992 and the largest Malaysia electricity utility company Tenaga Nasional Berhad (TNB) standard stated that, THD should be less than 5 % in the rated inverter output of the cable connected to Points of Common Coupling (PCC). Moreover, the solar irradiance in Malaysia varies daily and also throughout the year. The consequence of low irradiance level is that the output of the PV array is low and thus the input of the inverter relatively becoming low. The inverter exhibit large non-linearity when the inverter is operating at low power input during the low level of solar irradiance. The THD in a GCPV system is influenced by the solar irradiance due to the inversely proportional relationship between solar irradiance and THD. In addition, other main concerns in the GCPV system are switching losses of the switching devices in the inverter. The effectiveness of a system can improve by keeping the switching losses as low as possible. Pulse Width Modulation (PWM) techniques has its own benefits such as easy to implement and control, compatible with today's digital microprocessor, no additional components needs to be added to obtain control of the output voltage and lastly, lower harmonics can be eliminated or minimized. In this research, the main objective is to carry out research to minimize harmonics and switching loss reduction in the GCPV system. A GCPV system model in MATLAB/Simulink is used as the platform to implement continuous PWM (CPWM) and discontinuous PWM (DPWM) in the inverter control to investigate the effect of PWM switching frequency selection on THD and switching losses performance at different level of solar irradiance. The techniques were compared and CPWM is suggested as the recommended solution. This is due to the lower THD value obtained when CPWM applied in the inverter control. Additionally, the THD when DPWM applied is higher compared to CPWM at all solar irradiance levels. The appropriate minimum switching frequency of the PWM at different solar irradiance level that meet the standard THD requirement with minimum switching losses is proposed in this thesis. The appropriate switching frequency value for each of the solar irradiance ranges are $f_{sw}1$ = 12600.00 Hz during 200 – 400 W/m², $f_{sw}2$ = 5000.00 Hz when 401 – 600 W/m², $f_{sw}3$= 1746.00 Hz throughout 601 – 800 W/m² and $f_{sw}4$ = 1545.50 Hz for 801 – 1000 W/m² solar irradiance level. Meanwhile, DPWM required higher switching frequency to meet the standard THD and thus lead to higher switching losses in the system. The key finding in this investigation is the appropriate selection of switching frequency of the PWM may decrease the THD content at different solar irradiance level.

TABLE OF CONTENT

DECLARATION	
TITLE PAGE	
ACKNOWLEDGEMENTS	**ii**
ABSTRAK	**iii**
ABSTRACT	**iv**
TABLE OF CONTENT	**v**
LIST OF TABLES	**ix**
LIST OF FIGURES	**x**
LIST OF SYMBOLS	**xii**
LIST OF ABBREVIATIONS	**xiii**
CHAPTER 1 INTRODUCTION	**1**
1.1 Introduction	1
1.2 Renewable Energy	1
1.3 Photovoltaic System	4
1.4 Challenges in GCPV System	5
1.5 Problem Statement	6
1.6 Objectives	7
1.7 Scope of Research	8
1.8 Contribution	9
1.9 Thesis Organization	9

CHAPTER 2 LITERATURE REVIEW **11**

2.1 Introduction 11

2.2 Photovoltaic System 11

2.2.1 Factors Effect the Solar Cell Performance 13

2.2.2 Principle of Operation of GCPV System 14

2.2.3 Designing GCPV Systems 16

2.3 History of Converter 16

2.4 Inverter 17

2.4.1 Voltage Source Inverter 20

2.4.2 PWM-VSI Circuit Design 20

2.4.3 Voltage Source Inverter Basic Operation 22

2.5 Switching Devices 25

2.6 Power Quality Issues 27

2.7 Harmonics 29

2.8 Switching Losses 30

2.9 Pulse Width Modulation 31

2.9.1 Process to Generate PWM 37

2.9.2 Continuous PWM Concept 38

2.9.3 Discontinuous PWM Concept 40

2.10 Passive Filter 43

2.11 Previous Research 45

2.12 Conclusion 50

CHAPTER 3 METHODOLOGY **52**

3.1 Introduction 52

3.2 Research Methodology 53

3.2.1 GCPV System Configuration 55

3.2.2 PWM Implementation in GCPV System 58

3.2.3 Control of GCPV System Based on CPWM 61

3.2.4 Control of GCPV System Based on DPWM 63

3.2.5 FFT Analysis 64

3.2.6 Switching Losses Analysis 66

3.3 Conclusion 67

CHAPTER 4 RESULTS AND DISCUSSION 68

4.1 Introduction 68

4.2 Performance Analysis 68

4.2.1 Analysis of Output Power at Different Irradiance 69

4.2.2 Analysis THD at Different Irradiance 72

4.2.3 Analysis of Switching Frequency of PWM at Different Irradiance 78

4.2.4 Analysis of Switching Losses between PWM Techniques at Different Irradiance 86

4.3 Discussion 87

4.4 Conclusion 88

CHAPTER 5 CONCLUSION 89

5.1 Recommended Solution 91

5.2 Suggestion for Future Work 92

REFERENCES 93

PUBLICATIONS 101

APPENDIX A LIST OF CPWM CARRIER SIGNAL TRIAL TO FIND STANDARD THD **102**

APPENDIX B LIST OF DPWM CARRIER SIGNAL TRIAL TO FIND STANDARD THD **106**

APPENDIX C GCPV SYSTEM MODEL MATLAB/SIMULINK CIRCUIT **112**

APPENDIX D INVERTER CONTROL WITH CPWM **113**

APPENDIX E INVERTER CONTROL WITH DPWM **115**

LIST OF TABLES

Table 2.1	Summation of operation switches in 180° conduction modes	24
Table 2.2	Line to line voltages for 180° conduction mode	25
Table 2.3	Survey on the factors causes power quality problems	29
Table 2.4	Injection of zero sequence signals in the fundamental voltage of PWM	36
Table 3.1	Specification of SunPower SPR-X21-345-COM PV module	56
Table 3.2	Switching frequency selection based on solar irradiance range	58
Table 4.1	Average output current and power of the GCPV system model based on solar irradiance for CPWM and DPWM	70
Table 4.2	THD level for CPWM and DPWM based on different solar irradiance level at 1 kHz switching frequency	73
Table 4.3	Minimum switching frequency of the PWM and THD at different level of solar irradiance	84
Table 4.4	Results of increasing 33 % of CPWM and decreased 33 % of DPWM switching frequency to analyse switching losses	87
Table 5.1	Recommended switching frequency selection based on solar irradiance range	91

LIST OF FIGURES

Figure 1.1	Global top 10 solar PV markets total installed shares by the end of 2017	3
Figure 1.2	I-V curve of a PV module	5
Figure 1.3	Frequency occurrence of the global completely clear sky index	8
Figure 2.1	A typical SAPV system configuration	12
Figure 2.2	A typical GCPV system configuration	12
Figure 2.3	Temperature effect on voltage and current output of solar cell	13
Figure 2.4	Solar irradiance effect on voltage and current output	14
Figure 2.5	The main circuit topology of VSI	19
Figure 2.6	The main topology of CSI	19
Figure 2.7	Power converter structures of PWM-VSI	21
Figure 2.8	Three-phase VSI circuit with three-phase balance load connected	22
Figure 2.9	Line to neutral voltage for 180° conduction mode waveform	24
Figure 2.10	Line to line voltage waveform for 180° conduction mode	25
Figure 2.11	IGBT symbol	26
Figure 2.12	Output characteristic of IGBT	27
Figure 2.13	Noise free sinusoidal wave shape of voltage and current of a linear load	28
Figure 2.14	Non-sinusoidal wave shape with power quality problem for a non-linear load	28
Figure 2.15	Two groups of pulses involves in PWM	32
Figure 2.16	The process to generate PWM signal	33
Figure 2.17	Output signal of CPWM and DPWM	34
Figure 2.18	PWM types and categories	35
Figure 2.19	Graph of THD against mi for CPWM and DPWM signals (Va = SPWM, $Va1$ = TTHIPWM, $Va2$ = THIPWM, $Va3$ = DPWM1, $Va4$ = DPWM2)	36
Figure 2.20	Process to generate PWM	38
Figure 2.21	Three-phase THIPWM modulated wave	39
Figure 2.22	The process to produce a modulated modulating signal for TTHIPWM	39
Figure 2.23	The process to produce a modulated modulating signal for DPWM0, DPWM1 and DPWM2	41
Figure 2.24	Low pass filter response	44
Figure 2.25	High pass filter response	44

Figure 2.26	Low pass filter circuits	45
Figure 2.27	High pass filter circuit	45
Figure 3.1	Methodology flowchart	55
Figure 3.2	General block diagram of the research	56
Figure 3.3	PWM switching frequency selection	57
Figure 3.4	TTHIPWM modulating signal	59
Figure 3.5	DPWM2 modulating signal	59
Figure 3.6	Comparison between modulation and carrier signal of TTHIPWM	59
Figure 3.7	Comparison between modulation and carrier signal of DPWM2	60
Figure 3.8	TTHIPWM output signal	60
Figure 3.9	DPWM2 output signal	60
Figure 3.10	CPWM (TTHIPWM) subsystem	61
Figure 3.11	DPWM (DPWM2) subsystem	63
Figure 3.12	Powergui FFT analysis tool	66
Figure 4.1	Average output current of the GCPV system model based on solar irradiance for CPWM and DPWM control techniques	71
Figure 4.2	Average output power of the GCPV system model based on solar irradiance for CPWM and DPWM control techniques	72
Figure 4.3	THDi level for CPWM and DPWM based on different solar irradiance level at 1 kHz switching frequency	74
Figure 4.4	One cycle output current waveform for CPWM control technique	75
Figure 4.5	One cycle output current waveform for DPWM control technique	77
Figure 4.6	Harmonic spectrum of the current at PCC using CPWM control at different solar irradiance level	81
Figure 4.7	Harmonic spectrum of the current at PCC using DPWM control at different solar irradiance level	84
Figure 4.8	Minimum switching frequency of CPWM and DPWM carrier signal to obtain in standard $THDi$ at different level of solar irradiance	85
Figure 5.1	Block diagram of proposed CPWM as the recommended solution to meet the standard THD and minimize switching losses in a GCPV system	92

LIST OF SYMBOLS

ω	Angular Frequency
°C	Degree Celsius
%	Percentage
C	Capacitor
R	Resistor
L	Inductor
V	Voltage
I	Current
N	Neutral
Z	Impedance
A	Ampere
s	Second
t	Time
u	Instantaneous Voltage
i	Instantaneous Current
a, b, c	Three-phase Quantities
GW	Giga-Watt
GWp	Giga-Watt Peak
MW	Mega-Watt
MWp	Mega-Watt Peak
kWp	Kilo-Watt Peak
km	Kilo-meter
kHz	Kilo-Hertz
MHz	Mega-Hertz
W/m^2	Watt per Square Meter
V_s	Voltage Source
V_{dc}	Direct Current Voltage

LIST OF ABBREVIATIONS

APOD	Alternative Phase Opposition Displacement
BIPV	Building Integrate Photovoltaic
BJT	Bipolar Junction Transistor
BOS	Balance of System
c	Collector Terminal
CBSVPWM	Carrier Base Pulse Width Modulation
CPWM	Continuous Pulse Width Modulation
CSI	Current Source Inverter
DPWM	Discontinuous Pulse Width Modulation
DPWM2	Discontinuous PWM with π/3 Modulation Phase Angle
e	Emitter Terminal
FACTS	Flexible AC Transmission System
f_{co}	Cut Off Frequency
f_{s}	Switching Frequency
FFT	Fast Fourier Transform
FiT	Feed-in Tariff
g	Gate Terminal
G	Solar Irradiance
GC	Grid-connected
GCPV	Grid-connected Photovoltaic
GTO	Gate Turn-Off Thyristor
GUI	Graphical User Interface
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gate-Commutated Thyristor
I_{sc}	Short-circuit Current
m_i	Modulation Index
MOSFET	Metal Oxide Silicon Field Effect Transistor
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
NEM	Net Energy Metering

PCC	Point of Common Coupling
PCS	Power Conditioning System
PD	Phase Disposition
PF	Power Factor
POD	Phase Opposition Displacement
PV	Photovoltaic
RMS	Root Mean Square
PVPP	Photovoltaic Power Plant
SA	Stand-alone
SAPV	Stand-alone Photovoltaic
SEDA	Sustainable Energy Development Authority
SMPS	Switch-Mode Power Supplies
SPD	Surge Protection Device
SPWM	Sinusoidal Pulse Width Modulation
STC	Standard Test Condition
THD	Total Harmonic Distortion
THIPWM	Third Harmonic Injected Pulse Width Modulation
TTHIPWM	¼ Peak Value of Triangular Third Harmonic Injection Pulse Width Modulation
UPS	Uninterruptible Power Supply
V_c	Carrier Waveform Magnitude
V_{oc}	Open-circuit voltage
V_m	Modulated Waveform Magnitude
VSI	Voltage Source Inverter
VSPWM	Variable Structure PWM

REFERENCES

Aamri, F. E., Maker, H., Mouhsen, A., & Harmouchi, M. (2015). A new strategy to control the active and reactive power for single phase grid-connected PV inverter. *2015 3rd International Renewable and Sustainable Energy Conference (IRSEC)*, 1–6. https://doi.org/10.1109/IRSEC.2015.7455080

Abd Halim, H. (2013). *Three Phase Inverter Development Using Common Mode Voltage Pulse Width Modulation (PWM) Method* (Thesis, Universiti Tun Hussein Onn). Retrieved from http://eprints.uthm.edu.my/4693/1/HASMIZAR_BINTI_ABD_HALIM.pdf

Abdool, A., & Alwannan, K. (2014). Current harmonic generation of a modeled and simulated single phase grid connected PWM current controlled photovoltaic inverter. *2014 First International Conference on Green Energy ICGE 2014*, 89–95. https://doi.org/10.1109/ICGE.2014.6835403

Al-Shetwi, A. Q., & Sujod, M. Z. (2017, October). *Harmonic Distortion and Voltage Imbalance Study of Photovoltaic Power Plant Connected to the Malaysian Grid*. Presented at the 4th International Conference on Electrical, Control & Computer Engineering (InECCE), Langkawi, Malaysia.

Asiminoaei, L., Rodriguez, P., & Blaabjerg, F. (2008). Application of Discontinuous PWM Modulation in Active Power Filters. *IEEE Transactions on Power Electronics*, *23*(4), 1692–1706. https://doi.org/10.1109/TPEL.2008.924599

Ayub, M., Gan, C. K., & Kadir, A. F. A. (2014). The impact of grid-connected PV systems on Harmonic Distortion. *2014 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)*, 669–674. https://doi.org/10.1109/ISGT-Asia.2014.6873872

Badi, L. W. A., Zakaria, Z., Nordin, A. H. M., & Mustapa, R. F. (2014). Unbalanced faults analysis in grid - Connected PV system. *2014 IEEE International Conference on Power and Energy (PECon)*, 360–365. https://doi.org/10.1109/PECON.2014.7062471

Cai, W., Ren, H., Jiao, Y., Cai, M., & Cheng, X. (2011). Analysis and simulation for grid-connected photovoltaic system based on MATLAB. *2011 International Conference on Electrical and Control Engineering (ICECE)*, 63–66. https://doi.org/10.1109/ICECENG.2011.6056813

Cheng, H., Cao, W. s, & Ge, P. j. (2012). Forecasting Research of Long-Term Solar Irradiance and Output Power for Photovoltaic Generation System. *2012 Fourth International Conference on Computational and Information Sciences*, 1224–1227. https://doi.org/10.1109/ICCIS.2012.157

Dawidowski, P., Stosur, M., Szewczyk, M., & Balcerek, P. (2014). Reduction of THD by switching frequency optimization in three-level NPC inverter. *Research Gate*. https://doi.org/10.12915/pe.2014.08.04

Dugan, R. C., McGranaghan, M. F., Santoso, S., & Beaty, H. W. (2004). *Electrical Power System Quality* (Second). Retrieved from http://www.gcebargur.ac.in/sites/gcebargur.ac.in/files/lectures_desk/electrical_power_systems_quality.pdf

Ehmidat, M. M. (2013). *The Possible Contribution of Photovoltaic Systems to the Electricity Supply in some Districts in Palestine*. 107.

Fang, X. P., Cui, J. M., Liu, J., & Cao, M. Y. (2011). Detail research on the traditional inverter and Z-source inverter. *2011 International Conference on Applied Superconductivity and Electromagnetic Devices*, 318–321. https://doi.org/10.1109/ASEMD.2011.6145133

Fezzani, A., Mahammed, I. H., Drid, S., & Chrifi-alaoui, L. (2015). Modeling and analysis of the photovoltaic array faults. *2015 3rd International Conference on Control, Engineering Information Technology (CEIT)*, 1–9. https://doi.org/10.1109/CEIT.2015.7232983

Fourier Transforms - MATLAB & Simulink. (n.d.). Retrieved February 27, 2019, from https://www.mathworks.com/help/matlab/math/fourier-transforms.html

Grigoletto, F. B., Stefanello, M., Silva, G. S. da, & Pinheiro, H. (2016). Space vector pulse width modulation for Modular Multilevel Converters. *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society*, 2575–2581. https://doi.org/10.1109/IECON.2016.7793921

Hava, A. M., Kerkman, R. J., & Lipo, T. A. (1998). A high-performance generalized discontinuous PWM algorithm. *IEEE Transactions on Industry Applications*, *34*(5), 1059–1071. https://doi.org/10.1109/28.720446

Hava, Ahmet M. (1998). *Carrier Based PWM-VSI Drives in the Overmodulation Region*. University of Wisconsin, Madison.

Hicks, C., Baghzouz, Y., & Haddad, S. (2018). Power quality of residential PV system under low solar irradiance and off-grid operation. *2018 18th International Conference on Harmonics and Quality of Power (ICHQP)*, 1–5. https://doi.org/10.1109/ICHQP.2018.8378937

IGBT Structure and Circuit Working with Applications. (2015, June 3). Retrieved December 6, 2016, from Edgefxkits International website: http://efxkits.com/blog/igbt-circuit-working-with-applications/

Infineon Technologies AG. (2006). *Different PWM Waveforms Generation for 3-Phase AC Induction Motor with XC164CS*. München.

Insulated Gate Bipolar Transistor or IGBT Transistor. (2013, August 26). Retrieved October 5, 2017, from Basic Electronics Tutorials website: http://www.electronics-tutorials.ws/power/insulated-gate-bipolar-transistor.html

Jäger-Waldau, A. (2018). *PV Status Report 2018*.

Jayanth, K. G., Boddapati, V., & Geetha, R. S. (2018). Comparative study between three-leg and four-leg current-source inverter for solar PV application. *2018 International Conference on Power, Instrumentation, Control and Computing (PICC)*, 1–6. https://doi.org/10.1109/PICC.2018.8384793

Jianhui Wong, Y. S. L. (2014). Grid-connected photovoltaic system in Malaysia: A review on voltage issues. *Renewable and Sustainable Energy Reviews*, *29*, 535–545. https://doi.org/10.1016/j.rser.2013.08.087

Kamal EL-Sayed, S. (2017). Impact of Photovoltaic Tied to Electrical Grid System On Power Quality. *Journal of Electrical and Electronic Engineering*, *5*(2), 23. https://doi.org/10.11648/j.jeee.20170502.11

Khan, N., Siraj, A., Khan, J., Mahboob, F., & Haque, A. (2017). A simple and effective control of single phase solar inverter. *2017 International Conference on Power and Embedded Drive Control (ICPEDC)*, 190–195. https://doi.org/10.1109/ICPEDC.2017.8081085

Khanfara, M., Bachtiri, R. E., Hammoumi, K. E., & Boussetta, M. (2016). A comparison between two filters for PV inverter controlled to eliminate first harmonics. *2016 International Conference on Information Technology for Organizations Development (IT4OD)*, 1–6. https://doi.org/10.1109/IT4OD.2016.7479323

Kharjule, S. (2015). Voltage source inverter. *2015 International Conference on Energy Systems and Applications*, 537–542. https://doi.org/10.1109/ICESA.2015.7503407

Khatib, T., Mohamed, A., & Sopian, K. (2012). A Software Tool for Optimal Sizing of PV Systems in Malaysia. *Hindawi Publishing Corporation*, *2012*(Article ID 969248), 11. https://doi.org/10.1155/2012/969248

Khatri, M., & Kumar, A. (2017). Experimental Investigation of Harmonics in a Grid-Tied Solar Photovoltaic System. *INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH*, *Vol.7*(No.2), 901–907.

Kumar, N., Saha, T. K., Dey, J., & Barman, J. C. (2015). Modelling, control, and performance study of cascaded inverter based grid connected PV system. *IREC2015 The Sixth International Renewable Energy Congress*, 1–6. https://doi.org/10.1109/IREC.2015.7110884

Lacanette, K. (1991, April). *A Basic Introduction to Filters-Active, Passive, and Switched-Capacitor*. Retrieved from www.swarthmore.edu/NatSci/echeeve1/Ref/DataSheet/IntroToFilters.pdf

Mahyudin, B., & Abdul Malek, B. (2012). *National Survey Report of PV Power Applications in Malaysia 2011* (p. 26). Retrieved from file:///C:/Users/me/Downloads/nsr_2011_MYS.pdf

Mohammad Bagher, A., Abadi Vahid, M. M., & Mohsen, M. (2015). Types of Solar Cells and Application. *American Journal of Optics and Photonics*, *3*, 94–113. https://doi.org/10.11648/j.ajop.20150305.17

Mohanty, P., & Sahoo, S. (2010). *Analysis of Two-level and Three-level Inverters* (National Institute of Technology). Retrieved from http://ethesis.nitrkl.ac.in/1873/1/piyush.pdf

Nguyen, N. V., Nguyen, B. X., & Lee, H. H. (2011). An Optimized Discontinuous PWM Method to Minimize Switching Loss for Multilevel Inverters. *IEEE Transactions on Industrial Electronics*, *58*(9), 3958–3966. https://doi.org/10.1109/TIE.2010.2102312

Nordin, N. D., & Rahman, H. A. (2015). Pre-installation Design Simulation Tool for Grid-connected Photovoltaic System Using Iterative Methods. *Energy Procedia*, *68*, 68–76. https://doi.org/10.1016/j.egypro.2015.03.234

Nozadian, M. H. B., Ebrahimzadeh, F., Babaei, E., & Asl, E. S. (2017). Current-fed switched Z-source inverters. *2017 14th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, 769–772. https://doi.org/10.1109/ECTICon.2017.8096352

Oh, S., & Sunwoo, M. (2008). Variable structure PWM controller for high efficient PV inverters. *2008 IEEE International Conference on Sustainable Energy Technologies*, 933–938. https://doi.org/10.1109/ICSET.2008.4747141

Padure, P., Haraguta, C. I., Vintea, A., & Ghita, O. M. (2014). Evaluation method for harmonic distortion and power losses of photovoltaic systems using LabVIEW software. *2014 49th International Universities Power Engineering Conference (UPEC)*, 1–6. https://doi.org/10.1109/UPEC.2014.6934827

Parikh, P. R. (2017, July 9). *Operation Overview of Three Phase Inverter With 120°, 150° and 180° Conduction Mode*. 4. Retrieved from http://sdtechnocrates.com/IIIETEBMS2017/html/papers/III-ETEBMS-2017_ENG-EE8.pdf

Peng, F. Z. (2003). Z-source inverter. *IEEE Transactions on Industry Applications*, *39*(2), 504–510. https://doi.org/10.1109/TIA.2003.808920

Penkey, P., Alhajeri, F., & Johnson, B. K. (2016). Modeling, analysis and detection of faults in grid-connected PV systems. *2016 10th International Conference on Intelligent Systems and Control (ISCO)*, 1–5. https://doi.org/10.1109/ISCO.2016.7727038

Phap, V. M., Yamamura, N., Ishida, M., & Nga, N. T. (2017). Impact of solar irradiation on PV cell emulating system in series connection mode. *2017 International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*, 268–271. https://doi.org/10.1109/ICHVEPS.2017.8225955

Portal, E.-E. E. (2014, October 20). 9 Most Common Power Quality Problems | EEP. Retrieved April 4, 2017, from EEP - Electrical Engineering Portal website: http://electrical-engineering-portal.com/9-most-common-power-quality-problems

Pradhan, A., Ali, S. M., & Jena, C. (2013). Analysis of Solar PV cell Performance with Changing Irradiance and Temperature. *International Journal Of Engineering And Computer Science*, *2*(1), 214–220.

Prajapati, D., Ravindran, V., Sutaria, J., & Patel, P. (2014). A Comparative Study of Three Phase 2-Level VSI with 3-Level and 5-Level Diode Clamped Multilevel Inverter. *International Journal of Emerging Technology and Advanced Engineering*, *4*(4), 6.

Rahimi, K., Mohajeryami, S., & Majzoobi, A. (2016). Effects of photovoltaic systems on power quality. *2016 North American Power Symposium (NAPS)*, 1–6. https://doi.org/10.1109/NAPS.2016.7747955

Rajasekaran, R., Thulasi, J. A., & Glenn, J. A. (2016). Three phase solar uninterrupted power supply. *2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT)*, 4744–4747. https://doi.org/10.1109/ICEEOT.2016.7755620

Renu, V., & Surasmi, N. L. (2014). Optimal control of selective harmonic elimination in a grid-connected single-phase PV inverter. *2014 International Conference on Advances in Green Energy (ICAGE)*, 265–271. https://doi.org/10.1109/ICAGE.2014.7050175

Ruban, A. A. M., Hemavathi, N., & Rajeswari, N. (2012). Real time Harmonic Elimination PWM control for Voltage Source Inverters. *IEEE-International Conference On Advances In Engineering, Science And Management (ICAESM - 2012)*, 479–484.

Salim, M. S., Mohammed Najim, J., & Mohammed Salih, S. (2013). Practical Evaluation of Solar Irradiance Effect on PV Performance. *Energy Science and Technology*, *6*, 36–40. https://doi.org/10.3968/j.est.1923847920130602.2671

Sathishkumar, H., & Parthasarathy, S. S. (2016). Space vector pulse width modulation for DC-AC converter. *2016 Second International Conference on Science Technology Engineering and Management (ICONSTEM)*, 310–314. https://doi.org/10.1109/ICONSTEM.2016.7560968

Selvam, S. G. (2014). *Pre-Installed Economic Analysis Tool In Decision Making For Photovoltaic (PV) Systems Installation* (Universiti Teknologi Malaysia). Retrieved http://portal.fke.utm.my/fkelibrary/files/sriganeshalselvam/2014/941_SRIGANESHALSELVAM2014.pdf

Shaari, S., Omar, A. M., Haris, A. H., & Sulaiman, S. I. (2010a). *Solar Photovoltaic Power: Designing Grid-Connected Systems*.

Shaari, S., Omar, A. M., Haris, A. H., & Sulaiman, S. I. (2010b). *Solar Photovoltaic Power: Fundamental*.

Shah, N. (2013, May). *Harmonic in Power System - Causes, Effect and Control*.

SIEMENS.

Singh, S. K., Kumar, H., Singh, K., & Patel, A. (2014). A Survey and Study of Different Types of PWM Techniques Used in Induction Motor Drive. *International Journal of Engineering Science & Advanced Technology]*, *4*(1), 5.

SolarPower Europe, & Schmela, M. (2018). *Global Market Outlook For Solar Power / 2018 - 2022*. Retrieved from www.solarpowereurope.org

Sopian, K., Shaari, S., Amin, N., Zulkifli, R., Nizam, M., & Rahman, A. (2007). Performance of a grid-connected photovoltaic system in Malaysia. *ResearchGate*, *4*(1), 57–65.

Subsingha, W. (2016). A Comparative Study of Sinusoidal PWM and Third Harmonic Injected PWM Reference Signal on Five Level Diode Clamp Inverter. *Energy Procedia*, *89*, 137–148. https://doi.org/10.1016/j.egypro.2016.05.020

Sujod, M. Z. (2014). *Advanced Converter Control Techniques for Improving the Performance of DFIG based Wind Turbines* (Universität Duisburg-Essen). Retrieved from https://duepublico.uni-duisburg-essen.de/servlets/DerivateServlet/Derivate-36279/Sujod_Zahim_Diss.pdf

Sulaiman, Shahril Irwan, Rahman, T. K. A., Musirin, I., Shaari, S., & Sopian, K. (2012). An intelligent method for sizing optimization in grid-connected photovoltaic system. *Solar Energy*, *86*(7), 2067–2082. https://doi.org/10.1016/j.solener.2012.04.009

Sulaiman, S.I., Rahman, T. K. A., & Musirin, I. (2010). Design of grid-connected photovoltaic system using evolutionary programming. *2010 IEEE International Conference on Power and Energy (PECon)*, 947–952. https://doi.org/10.1109/PECON.2010.5697715

Sulaiman, S.I., Rahman, T. K. A., & Musirin, I. (2011). Artificial immune system for sizing grid-connected photovoltaic system. *Power Engineering and Optimization Conference (PEOCO), 2011 5th International*, 398–403. https://doi.org/10.1109/PEOCO.2011.5970448

Sulaiman, S.I., Rahman, T. K. A., Musirin, I., & Shaari, S. (2011). Sizing grid-connected photovoltaic system using genetic algorithm. *2011 IEEE Symposium on Industrial Electronics and Applications (ISIEA)*, 505–509. https://doi.org/10.1109/ISIEA.2011.6108763

Sunny, R., & Anto, R. (2013). Harmonics control and performance analysis of a grid connected photovoltaic system. *2013 International Conference on Advanced Computing and Communication Systems*, 1–6. https://doi.org/10.1109/ICACCS.2013.6938706

Winder, S. (2002). *Analog and Digital Filter Design* (Second Edition). United States of America: Elsevier Science.

Wu, Y., Shafi, M. A., Knight, A. M., & McMahon, R. A. (2011). Comparison of the Effects of Continuous and Discontinuous PWM Schemes on Power Losses of Voltage-Sourced Inverters for Induction Motor Drives. *IEEE Transactions on Power Electronics*, *26*(1), 182–191. https://doi.org/10.1109/TPEL.2010.2054837

Xplanator. (2017). *Three Phase Inverter under 180 degree operation and the asscociated waveforms*. Retrieved from https://www.youtube.com/watch?v=Jl8PHbv4KQs

Zahim, S. M., & Erlich, I. (2012). Control of DFIG based Wind Turbine Converter using Continuous and Discontinuous PWM: A Comparative Study. *IFAC Proceedings Volumes*, *45*(21), 542–547. https://doi.org/10.3182/20120902-4-FR-2032.00095

Zambri, M. K. M., Aras, M. S. M., Khamis, A., & Hairi, mohd H. (2016). Investigating the Impact of Photovoltaic Connection to the Malaysian Distribution System. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC), 8*(7), 23–28.

Zhao, X., & Liu, S. (2012). A Research of Harmonics for Multiple PV Inverters in Grid-Connected. *2012 Asia-Pacific Power and Energy Engineering Conference*, 1–4. https://doi.org/10.1109/APPEEC.2012.6307197